(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 1 293 807 A1

(12) # EUROPEAN PATENT APPLICATION

(43) Date of publication:
19.03.2003 Bulletin 2003/12

(51) Int Cl.7: **G02B 3/14**

(21) Application number: **02252089.4**

(22) Date of filing: **22.03.2002**

(84) Designated Contracting States:
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE TR
Designated Extension States:
AL LT LV MK RO SI

(30) Priority: **13.09.2001 US 951637**

(71) Applicant: **LUCENT TECHNOLOGIES INC.**
Murray Hill, New Jersey 07974-0636 (US)

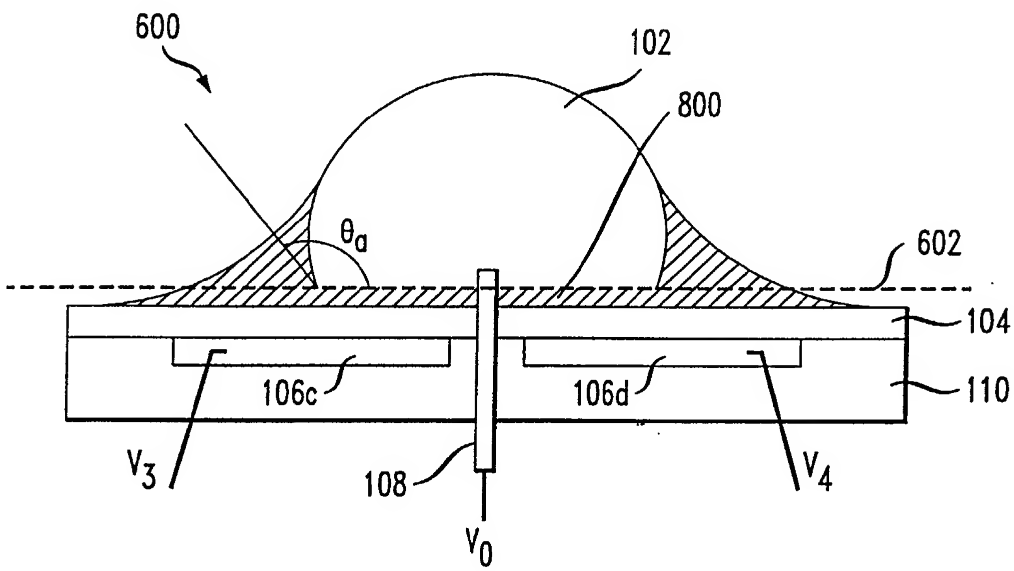
(72) Inventors:
- **Kroupenkine, Timofei N.**
  Piscataway, NJ 08854 (US)
- **Yang, Shu**
  North Plainfield, NJ 07060 (US)

(74) Representative:
Watts, Christopher Malcolm Kelway, Dr. et al
Lucent Technologies (UK) Ltd,
5 Mornington Road
Woodford Green Essex, IG8 0TU (GB)

(54) **Tunable liquid microlens with lubrication assisted electrowetting**

(57) A tunable liquid microlens includes an insulating layer, a droplet of a transparent conducting liquid, and a lubricating layer disposed on a first surface of the insulating layer and between the droplet and the insulating layer. The microlens also includes a plurality of electrodes insulated from the droplet by the insulating layer and the lubricating layer, the plurality of electrodes being disposed such that they may be selectively biased to create a respective voltage potential between the droplet and each of the plurality of electrodes, whereby an angle between the droplet and a plane parallel to the first surface of the insulating layer may be varied and the droplet may be repositioned relative to the insulating layer.

FIG. 6



EP 1 293 807 A1

Description

FIELD OF THE INVENTION

[0001] The present invention relates to microlenses, and more particularly to liquid microlenses.

DESCRIPTION OF THE RELATED ART

[0002] Most tunable microlenses are either gradient index (GRIN) lenses with the refractive index controlled electrostatically or flexible polymeric lenses with the shape controlled mechanically. Both technologies have inherent limitations that impose severe restrictions on the performance of these existing tunable microlenses.

[0003] Tunable gradient index lenses have inherent limitations associated with the relatively small electro-optic coefficients found in the majority of electro-optic materials. This results in a small optical path modulation and, therefore, requires thick lenses or very high voltages to be employed. In addition, many electro-optic materials show a strong birefringence that causes polarization dependence of the microlens properties.

[0004] Mechanically adjustable flexible lenses typically have a substantially wider range of tunability than the gradient index lenses. However, they require external actuation devices, such as micropumps, to operate. Microintegration of such devices involves substantial problems, especially severe in the case where a two-dimensional array of tunable microlenses is required.

[0005] Attempts have also been made to use other technologies to produce tunable microlenses, such as liquid microlenses controlled through self assembled monolayers (SAMs). Some of these attempts are described in U.S. Patent No. 6,014,259 to Wohlstadter, issued January 11, 2000, the entirety of which is hereby incorporated by reference herein. Microlenses utilizing self assembled monolayers, however, also suffer from several problems, including severe limitations on material selection and strong hysteresis leading to the failure of the microlens to return to an original shape after a tuning voltage is disconnected. Additionally, none of the above-described microlenses allow for both lens position adjustment and focal length tuning.

[0006] A tunable liquid microlens is proposed in the Applicants' copending U.S. Patent Application Serial No. 09/884,605 to Timofei N. Kroupenkine and Shu Yang, filed June 19, 2001, entitled "Tunable Liquid Microlens." The tunable liquid microlens of the '605 application allows for both lens position adjustment and focal length tuning. In one embodiment of an exemplary tunable liquid microlens described in the '605 application, a droplet of a transparent conducting liquid is disposed on a supporting substrate including a fluorinated polymer, such as a highly fluorinated hydrocarbon. This configuration provides a liquid microlens that is highly tunable and which does not suffer from the well known hysteresis and stick-slip effects, which can occur during electrowetting.

SUMMARY OF THE INVENTION

[0007] While the '605 application provides for an exemplary tunable liquid microlens, there remains a need for a tunable liquid microlens that provides for even greater freedom in material selection and excellent tunability while reducing or eliminating contact angle hysteresis and stick-slip effects. This is achieved by an improved tunable liquid microlens that includes an insulating layer, a droplet of a transparent conducting liquid, and, in accordance with the principles of the invention, a lubricating layer disposed on a first surface of the insulating layer and between the droplet and the insulating layer. The microlens also includes a plurality of electrodes insulated from the droplet by the insulating layer and the lubricating layer, the plurality of electrodes being disposed such that they may be selectively biased to create a respective voltage potential between the droplet and each of the plurality of electrodes, whereby an angle between the droplet and a plane parallel to the first surface of the insulating layer may be varied and the droplet may be repositioned relative to the insulating layer.

[0008] The tunable liquid microlens with lubrication assisted electrowetting allows for both lens position adjustment and focal length tuning. In addition, the tunable liquid microlens provides for even greater freedom in material selection with no contact angle hysteresis or stick-slip effect while providing excellent tuning control.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The accompanying drawings illustrate preferred embodiments of the invention, as well as other information pertinent to the disclosure, in which:

FIG. 1A is a diagrammatic representation of light waves passing through a liquid microlens;
FIG. 1B is a diagrammatic representation of the electrowetting phenomena;
FIG. 2A is a diagrammatic representation of a tunable liquid microlens of the present invention;

FIG. 2B illustrates one exemplary electrode pattern for a tunable liquid microlens of the present invention;
FIGS. 2C-2E illustrate the reaction of the tunable liquid microlens of the present invention to selected biasings of the electrodes of FIG. 2B;
FIGS. 3A-C are diagrammatic representations of exemplary embodiments of a tunable liquid microlens according to the present invention;
FIG. 4 illustrates an optical system including a tunable liquid microlens of the present invention;
FIG. 5 is a diagram of an apparatus including a planar waveguide and a tunable liquid microlens of the present invention.
FIG. 6 is a diagrammatic representation of an exemplary embodiment of a tunable liquid microlens of the present invention utilizing a lubrication layer;
FIG. 7 is a diagrammatic representation of another exemplary embodiment of a tunable liquid microlens of the present invention utilizing a lubrication layer; and
FIG. 8 is a plot illustrating the effect of material selection on the microlens of FIG. 6 and FIG. 7.

[0010] It should be understood that the figures are included for illustrative purposes and are not drawn to scale.

DETAILED DESCRIPTION

[0011] Before the tunable liquid microlens of the present invention is described in detail, a description of a liquid microlens generally and a description of the electrowetting phenomena are first provided.

[0012] Referring to FIG. 1A, a liquid microlens 10 is shown. The microlens 10 includes a small droplet 12 of a transparent liquid, such as water, typically (but not necessarily) with a diameter from several micrometers to several millimeters. The droplet 12 is disposed on a transparent substrate 14. The substrate is typically hydrophobic or includes a hydrophobic coating. The liquid and substrate need only be transparent to light waves having a wavelength within a selected range. Light waves are illustrated by reference numeral 16. Light waves pass through liquid microlens 10 and focus at a focal point or focal spot (designated by reference numeral 18) in a focal plane that is a focal distance "f" from the contact plane between droplet 12 and substrate 14.

[0013] The contact angle "θ" between the droplet 12 and the substrate 14 is determined by interfacial surface tensions (also called interfacial energy) "γ", generally measured in milli-Newtons per meter (mN/m). As used herein, γ_{S-V} is the interfacial tension between the substrate and the air, gas or other liquid that surrounds the substrate 14, γ_{L-V} is the interfacial tension between the droplet 12 and the air, gas or other liquid that surrounds the droplet 12, and γ_{S-L} is the interfacial tension between the substrate 14 and the droplet 12. The contact angle θ may be determined from equation (1):

$$\text{Equation (1)} \qquad \cos\theta = \frac{\gamma_{S-V} - \gamma_{S-L}}{\gamma_{L-V}}$$

[0014] The radius "R" in meters of the surface curvature of droplet 12 is determined by the contact angle θ and the droplet volume in cubic meters (m^3) according to equation (2) as follows:

$$\text{Equation (2)} \qquad R^3 = \frac{3\ \text{Volume}}{\pi(1-\cos\theta)(2-\cos^2\theta-\cos\theta)}$$

[0015] The focal length in meters is a function of the radius R and the refractive indices "n", where n_{Liquid} is the refractive index of the droplet 12 and n_{Vapor} is the refractive index of the air, gas or other liquid that surrounds the droplet 12. The focal length f may be determined from equation (3):

$$\text{Equation (3)} \qquad f = \frac{R}{n_{Liquid} - n_{Vapor}}$$

[0016] The refractive index of the substrate is not important because of the parallel entry and exit planes for the light waves. The focal length of the microlens 10, therefore, is a function of the contact angle θ.

[0017] FIG. 1B demonstrates that the phenomena of electrowetting may be used to reversibly change the contact angle θ between a droplet 22 of a conducting liquid (which may or may not be transparent) and a dielectric insulating layer 24 having a thickness designated as "d" and a dielectric constant ε_r. An electrode, such as metal electrode 26,

is positioned below the dielectric layer 24 and is insulated from the droplet 22 by layer 24. The droplet 22 may be, for example, a water droplet, and the substrate 24 may be, for example, a Teflon/Parylene surface.

[0018] When no voltage difference is present between the droplet 22 and the electrode 26, the droplet 22 maintains a shape defined by the volume of the droplet 22 and contact angle θ_1, where θ_1 is determined by the interfacial tensions γ as explained above. The dashed line 28 illustrates that the droplet 22 spreads equally across layer 24 from its central position relative to electrode 26 when a voltage is applied between electrode 26 and droplet 22. The voltage may range from several volts to several hundred volts. Specifically, the contact angle θ decreases from θ_1 to θ_2 when the voltage is applied, regardless of polarity, between electrode 26 and the droplet 22. The amount of spreading, i.e., as determined by the difference between θ_1 and θ_2, is a function of the applied voltage V. The contact angle θ_2 can be determined from equation (4):

$$\text{Equation (4)} \qquad \cos\theta\,(V) = \cos\theta\,(V{=}0) + \frac{\varepsilon_0\ \varepsilon_r}{2d\gamma_{L\text{-}V}}\,V^2.$$

where cos θ (V=0) is the contact angle between the insulating layer 24 and the droplet 22 when no voltage is applied between the droplet 22 and electrode 26, $\gamma_{L\text{-}V}$ is the droplet interfacial tension described above, ε_r is the dielectric constant of the insulating layer, and ε_0 is 8.85 x 10^{-12} F/m - the permittivity of a vacuum.

[0019] FIGS. 2A and 2B illustrate a tunable liquid microlens that is capable of varying both position and focal length as described hereafter. Referring to FIG. 2A specifically, a tunable liquid microlens 100 includes a droplet 102 of a transparent, conductive liquid disposed on a first surface of a transparent, dielectric insulating layer 104. The insulating layer 104 may be, for example, a polyimide coated with a fluorinated polymer, such as a highly fluorinated hydrocarbon. In any case, the insulating layer 104 should provide predetermined values of contact angle and contact angle hysteresis and have a high dielectric breakdown strength that is appropriate for the applied voltages. The microlens 100 includes a plurality of electrodes 106a-106d insulated from the droplet 102 by insulating layer 104. The microlens 100 may also include a transparent supporting substrate 110 which supports the electrodes 106 and insulating layer 104. The electrodes 106 and the supporting substrate 110 may be, for example, gold and glass, respectively.

[0020] FIG. 2B is a top plan view of an exemplary configuration for the electrodes 106a-106d. Although one configuration of four electrodes 106a-106d is shown, other numbers, combinations and patterns of electrodes 106 may be utilized depending upon the desired level of control over the tuning of the microlens 100. Each electrode 106a-106d is coupled to a respective voltage V_1-V_4 and droplet 102, which is centered initially relative to the electrodes 106, is coupled to a droplet electrode 108, which is coupled to a voltage Vo.

[0021] When there is no voltage difference between the droplet 102 and any of the electrodes 106 (i.e., V_1=V_2=V_3=V_4= Vo) and the droplet is centered relative to the electrodes 106 and quadrants I through IV, the droplet 102 assumes a shape as determined by contact angle θ and the volume of droplet 102 in accordance with equations (1)-(3) explained above. FIG. 2C illustrates this initial position of droplet 102 with a dashed line. The position of droplet 102 and the focal length of the microlens 100 can be adjusted by selectively applying a voltage potential between the droplet 102 and the electrodes 106. If equal voltages are applied to all four electrodes, i.e., V_1=V_2=V_3=V_4≠Vo, then the droplet 102 spreads equally within quadrants I, II, III, and IV (i.e., equally along lateral axes X and Y) as shown by the dashed line of FIG. 2D. In essence, the contact angle θ between the droplet 102 and insulating layer 104 decreases. In so doing, the focal length of the microlens 100 increases from the focal length of the microlens at the initial contact angle θ (i.e., when V_1=V_2=V_3=V_4=Vo).

[0022] FIG. 2E illustrates that the lateral positioning of the droplet 102 along the X and Y axes can also be changed relative to the initial location of the droplet 102 on the first surface of insulating layer 104 by selectively biasing the electrodes 106 relative to droplet 102. For example, by making V_1=V_3=Vo and by making V_2 greater than V_4, the droplet 102 is attracted toward the higher voltage of electrode 106b and moves toward quadrant II. By adjusting the lateral position of the droplet 102, the lateral position of the focal spot of the microlens in the focal plane is also adjusted.

[0023] It should be apparent from the above examples that the electrodes 106 can be selectively biased relative to the droplet electrode (and thus droplet 102) in any number of combinations in order to adjust the contact angle θ and thereby to modify the focal length of the microlens 100. Likewise, the electrodes 106 can be selectively biased in any number of combinations to reposition the droplet 102 relative to an initial location on the insulating layer 104, whereby the lateral position of the focal spot of the microlens is adjusted. Therefore, the microlens allows for the adjustment of the focal spot in three dimensions - the position of the focal spot as determined by the focal length and the lateral position of the focal spot in the focal plane that is parallel with the first surface of the microlens and is a focal length away from the microlens.

[0024] FIG. 3A illustrates one manner of coupling the droplet 102 to a voltage Vo, such as ground or other constant voltage level. Microlens 100a may include a supporting substrate 110a which includes a conductive glass, such as indium tin oxide glass. The conductive glass is coupled to voltage Vo and an electrode 116 couples the substrate 110a

to the droplet 102. The electrode 116 and supporting substrate 110a may collectively be considered a droplet electrode. FIG.3A also illustrates that the insulating dielectric layer 104 may include a dielectric layer 114 and a hydrophobic coating layer 112. The coating layer 112 should provide a relatively high contact angle θ. One example is a highly fluorinated polymer, such as a Teflon or other material with chemical structure similar to Teflon. Low surface energy materials, such as silicon-containing polymers or molecules are also appropriate. In one embodiment, insulating layer 104a includes a coating layer 112 that is a Teflon film disposed on a polyimide dielectric layer 114.

[0025] In an alternative embodiment of a microlens 100B shown in the isometric view of FIG. 3B, droplet electrode 116 may be, for example, a gold electrode evaporated or otherwise deposited on a first surface of an insulating layer 104 (not shown) in an area or plurality of areas that ensures that the electrode 116 maintains contact with the droplet 102 when the droplet 102 changes position along the first surface of the insulating layer 104. Although the electrode 116 is disposed to maintain contact with the droplet 102 when the droplet 102 changes position, the droplet 102 is substantially disposed on the first surface of insulating layer 104. The microlens 100B may include a supporting substrate 110a that need not be conductive and may be, for example, non-conductive glass that serves as a mechanical support layer for insulating layer 104 and the electrodes 106. In that case, droplet electrode 116 may be coupled directly to a voltage Vo. Alternatively, the supporting layer 110a may be a conductive glass substrate that is coupled to a voltage Vo. In that embodiment, the droplet electrode 116 may be coupled to the supporting layer 110a. Also shown in FIG. 3B are electrodes 106a-106d and their respective power leads 118a-118d, which are coupled to voltages V_1-V_4, respectively. Although an insulating layer 104 is not shown in FIG. 3B, this is for illustrative purposes only, and an insulating layer 104 insulates the droplet 102 and electrode 116 from electrodes 106a-106d.

[0026] FIG. 3C illustrates an exemplary embodiment of a tunable liquid microlens 100C where no electrode 116 is required, thereby reducing any potential interference with the microlens from electrode 116. Microlens 100C includes droplet 102 disposed on a first surface of an insulating layer 104b. Microlens 100C also includes a transparent conductive supporting layer 110a which serves as a droplet electrode disposed along a second surface of insulating layer 104b opposite the first surface of insulating layer 104b. Microlens 100C is shown in cross-section to illustrate that insulating layer 104b includes an aperture 118 defined by the insulating layer 104b and continuing there through. The droplet 102 occupies at least a part of the aperture 118, thereby placing the droplet 102 in electrical communication with the droplet electrode, i.e., supporting substrate 110a. The supporting substrate 110a is then coupled to a voltage Vo. In this exemplary embodiment, the insulating layer 104b also does not have to be transparent as long as the aperture is wide enough so that the light that penetrates through the aperture is sufficient for the particular application.

[0027] The liquid droplet may be any liquid which is transparent to the desired wavelength and which is intrinsically conductive or which can be made conductive, such as through the use of various additive. Typical examples includes aqueous solutions of various salts. The electrodes may be any solid conductive materials, which may or may not be transparent, such as gold, aluminum, or indium tin oxide glass. The insulating layer may be any solid dielectric or a set of solid dielectrics that provide high enough dielectric strength and predefined values of contact angle and contact angle hysteresis. The insulating layer may or may not be transparent. Examples include solid polymers, such as polyimide and parylene. The supporting substrate may be any substrate that is transparent to a given wavelength, such as glass or a solid polymer. The applied voltages depend upon the selected materials, the layout of the microlens, and the desired change in the contact angle, as guided by the above equations (1)-(4). Typical voltages may vary between 0 volts and approximately 200 volts, although the acceptable voltages are not limited to this range.

[0028] In one embodiment, the liquid droplet of the microlens may be substantially encompassed by a liquid that is immiscible with the droplet. The surrounding liquid may help to prevent the microlens droplet from evaporating. When the droplet is water based, various oils or high molecular weight alcohols (e.g., pentanol, octanol, etc.) may be used.

[0029] The microlens 100C of FIG. 3C was tested. The microlens included a droplet 102 including 20 μl of 0.01 aqueous KNO_3 solution. The insulating layer 104b included a 3 μm thick polyimide layer coated with a very thin ($\simeq$ 0.02 to 2 μm) layer of a highly fluorinated polymer that provided an initial contact angle of approximately 109°. A set of four gold electrodes 106 were arranged as shown in FIGS. 2B and 3C. The microlens included an ITO (indium tin oxide) glass plate as a conductive transparent supporting substrate 110a shown in FIG. 3C. Operating voltages between 0V and approximately 150V were applied.

[0030] A reversible adjustment of the focal length of the microlens within the range between 6 mm and 8 mm was demonstrated. Also, an adjustment of a microlens position within a range of about 3 mm in any lateral direction along the surface of the insulating layer was demonstrated. It should be understood that the obtained results do not represent the limits of the microlens, but rather serve to indicate that a tunable liquid microlens may be fabricated which can vary both focal distance length and focal spot position.

[0031] From the above, it should be apparent that the described microlens may be designed to have a desired contact angle θ when there is no voltage difference between the droplet and the electrodes 106 and a desired contact angle hysteresis. This may be achieved by selecting appropriate materials, dimensions, and volumes as guided by the equations set forth above. The microlens therefore allows substantial freedom in both droplet curvature and position control, thereby leading to a wide range of tunability in the microlens, focal length, focal spot position, and numerical aperture.

[0032] One of ordinary skill should realize that the microlens of the present invention may be utilized in several optoelectronic applications. For example, the microlens may be used to achieve optimal coupling between an optical signal transmitter 204, such as a laser, and an optical signal receiver 202, such as a photodetector. This is illustrated in FIG. 4. It should be understood from FIG. 4 that the optical signal from transmitter 204 is diverging and will be focused behind the focal plane 206. The lens focal distance and lateral positioning of the focal spot 208 within focal plane 206 of the microlens 100 may be adjusted as described above by selectively biasing the plurality of electrodes 106 to achieve this optimal coupling. The biasing electrodes can be selectively biased until the highest power is detected at receiver 202 - representing the optimal coupling between transmitter 204 and receiver 202. Currently, optoelectronic packages, i.e., physical apparatuses incorporating optoelectronic components such as lasers and/ or photodetectors, are calibrated by physically moving component parts to achieve optimal coupling. This process can be slow and quite expensive. By including at least one microlens of the present invention in the apparatus, the need to physically align component parts to achieve optimal coupling is eliminated. Rather, the focal length and lateral position of the focal spot of the microlens of the present invention may be adjusted to redirect an optical signal from a transmitter to a fixed receiver.

[0033] In another exemplary application illustrated in FIG. 5, a microlens 100, or plurality of microlenses of the present invention, is utilized to couple an optoelectronic component, such as a photodetector 506 that is surface-mounted through a ball grid array 512 on a printed circuit board 500, with an embedded planar waveguide 504. Light propagates through a core 502 of planar waveguide 504 as indicated by the directional arrows. The light is reflected by a mirror edge 508 toward a top surface 510 of the printed circuit board 500. A tunable liquid microlens 100 is disposed on the top surface 510 of the printed circuit board 500 and directs the light 502 toward photodetector 506 in the direction shown. The electrodes of the tunable liquid microlens 100 may be selectively biased to adjust the focal length and lateral focal spot position of the microlens 100 in order to tune the microlens 100 to optimize the transmission of the light from the planar waveguide 504 to the photodetector 506. The shape of the microlens is maintained by the application of the appropriate voltage.

[0034] FIGS. 6 and 7 illustrate another exemplary embodiment of a tunable liquid microlens that is capable of varying both focal spot position and focal length, while increasing the range of materials that may be utilized in a tunable liquid microlens. First, an overview of the "stick-slip" phenomenon is briefly provided. As mentioned in the overview of electrowetting provided above in connection with FIG. 1B, the contact angle θ between layer 24 and the droplet 22 may be changed by applying a voltage between the electrode 26 and the droplet 22. A stick-slip phenomenon can cause the contact angle θ to change under the applied voltage incrementally, rather than in a smooth transition from the initial contact angle to the final contact angle. While a voltage is applied, the droplet can "stick" to the surface of the substrate 24 and maintain a first contact angle θ_X for a period of time. Eventually, under the applied voltage, the droplet "slips" to define a new contact angle θ_Y. These incremental jumps can occur several times during a transition between an initial contact angle and a final contact angle, depending upon the applied voltage. Because the droplet initially sticks and then slips, the contact angle θ changes incrementally and no contact angles can easily be achieved that fall between, for example, θ_X and θ_Y.

[0035] It is believed that the stick-slip phenomenon is mainly caused by inhomogenaities, impurities or contaminants in the substrate 24, leading to localized inconsistencies in interfacial tensions between the droplet 22 and the substrate 24. The stick-slip phenomenon can limit the ability to accurately tune a microlens utilizing electrowetting.

[0036] The other phenomenon closely related to the stick-slip phenomenon is a contact angle hysteresis phenomenon. Contact angle hysteresis refers to the difference between the contact angle of the advancing droplet (such as the angle obtained at a given voltage Vo during the voltage increase from, for example, 0V to Vo) and the retracting droplet (such as the contact angle obtained at the same voltage Vo but during the voltage decrease from, for example, Vo to 0V). Contact angle hysteresis leads to the dependence of the droplet contact angle on the droplet history - that is whether the voltage was decreasing or increasing - and complicates the droplet control through electrowetting. Also, if the hysteresis is high enough, it can prevent the droplet from returning to its original shape when the voltage is removed. Note, however, that although the stick-slip and contact angle hysteresis are closely related phenomena, they are not identical. In particular, it is possible to obtain in certain situations the contact angle hysteresis behavior that is not associated with any appreciable stick-slip behavior.

[0037] With respect to the exemplary tunable liquid microlenses described in connection with FIGS. 2A to 3C, any appreciable contact angle hysteresis and stick-slip may be avoided by selecting an appropriate insulating layer that includes, for example, a fluorinated polymer, such as a highly fluorinated hydrocarbon. Although this is an acceptable solution to avoiding the hysteresis and stick-slip problems, it is also desirable to improve the range of materials that are available to serve as insulating layers in the tunable liquid microlenses of the present invention.

[0038] Referring to FIG. 6, a tunable liquid microlens 600 is illustrated. The tunable liquid microlens 600 has the same basic structure as the microlens 100 of FIG. 2A and like components share the same reference numerals. Tunable liquid microlens 600, however, includes a relatively thin lubricating layer 800 (illustrated in cross-hatch) disposed on a first surface of insulating layer 104. The lubricating layer 800 is spread across the first surface of the insulating layer

104 and droplet 102 is disposed on the lubricating layer 800 such that the lubricating layer 800 is between insulating layer 104 and droplet 102.

[0039] An angle θ_a is generally defined between the droplet 102 and a plane 602 that is parallel with the first surface of the insulating layer 104. Like contact angle θ described in connection with FIGS. 2A-3C, angle θ_a can be made to change by selectively applying a voltage between electrodes 106 and droplet 102. In this manner, the focal length of the microlens 600 is tunable. The lubricating layer separates the droplet 102 from the insulating layer 104 and provides spatially uniform interfacial tension between the droplet 102 and the lubricating layer 800. A wider range of materials may be selected for insulating layer 104 because the droplet 102 does not contact any localized inhomogenaities or contaminants that would otherwise lead to contact angle hysteresis and the stick-slip effect between a droplet 102 and an insulating layer 104.

[0040] Like the microlenses of FIGS. 2A-3C, the microlens can also vary its position relative to insulating layer 104, i.e., along plane 602, by selectively biasing electrodes 106. In this manner, the focal spot position of the tunable liquid microlens 600 may be varied.

[0041] FIG. 6 illustrates that the insulating layer 800 may be implemented as a liquid layer that separates the liquid droplet 102 from the insulating layer 104 when droplet 102 is disposed on lubricating layer 800. In another exemplary tunable liquid microlens 700, illustrated in FIG. 7, the microlens 700 includes a surrounding liquid 802 (shown in cross-hatch) that includes lubricating layer 800, that is immiscible with droplet 102, and that substantially surrounds the surface of the droplet 102.

[0042] An angle θ_b is defined between the droplet 102 of microlens 700 and a plane 604 that is parallel with the first surface of the insulating layer 104. Like microlens 600, the angle θ_b may be varied by selectively biasing electrodes 106 relative to the droplet 102 in order to vary the focal length of the microlens 700. Also, the droplet 102 may be repositioned relative to the insulating layer 104, i.e., along plane 604, to change the focal spot position of the microlens 700.

[0043] As shown in FIGS. 6 and 7, a lubricating layer 800 can either be spread along the first surface of insulating substrate 104 or the microlens droplet 102 can be completely immersed in a liquid 802 that includes the lubricating layer 800. The lubricating layer 800 should be transparent to a desired wavelength of light, although this need not be the case if a structure with an aperture 118 shown in FIG. 3C is utilized. In this case the lubricating layer does not occupy the aperture 118 if the surface energy of the material selected for the supporting conductive layer exceeds a certain threshold value. This happens because the lubricant can wet (i.e., provide zero contact angle) only the surfaces with a surface energy below a certain threshold as further explained below. The lubricating layer should be dielectric and should be selected in such as way that it wets the dielectric substrate 104 underneath the microlens droplet 102. An exemplary lubricating layer 800 includes a low surface energy liquid that is immiscible with droplet 102. One exemplary liquid is a silicone oil. A number of fluorinated organic liquids may be used as well, such as fluorosilicones such as FMS-131, FMS-221 (poly(3,3,3-trifluoropropylmethylsiloxane)) and SIB1816.0 [Bis(tridecafluorooctyl)tetramethylsiloxane] available from Gelest, Inc of Tullytown, Pennsylvania. The wetting of the substrate by the lubricating layer can either be complete or with a finite, but small, contact angle between the lubricating layer and the insulating substrate 104. In both cases, the lubricating layer 800 naturally forms a thin layer underneath the microlens droplet 102 and substantially prevents contact angle hysteresis and "stick-slip" behavior.

[0044] Both the microlense 600 of FIG. 6 and the microlens 700 of FIG. 7 show a lubricating layer 800 separating the droplet 102 from the insulating layer 104. In order to ensure that the lubricating layer 800 forms a separation layer between the droplet 102 and the insulating layer 104, materials having appropriate surface energies γ must be selected. Of course, these materials may be selected somewhat by trial and error, but the following principles may also be utilized.

[0045] Assuming for example the simplest theoretical scenario: a droplet 102 is in a spherical shape, as shown in FIG. 7, when no voltage is applied between the droplet 102 and the electrodes 106, i.e., the surface of the droplet 102 is completely surrounded by a fluid 802 and the droplet 102 forms an angle of 180° with a plane 604 that is parallel with the first surface of the insulating layer 104. The angle θ_b when no voltage is applied is initially determined by the interfacial tension between the substrate 104 and the droplet 102($\gamma_{S\text{-}L}$), the interfacial tension between the substrate 104 and the lubricating liquid 800 ($\gamma_{S\text{-}F}$), and the interfacial tension between the droplet 102 and the lubricating fluid 802 ($\gamma_{L\text{-}F}$). The angle θ_b can be determined by equation (5) as follows:

$$\text{Equation (5)} \qquad \cos\theta_b = \frac{\gamma_{S\text{-}F} - \gamma_{S\text{-}L}}{\gamma_{L\text{-}F}}$$

where γ_{ij} (i,j = S, L or F) are interfacial surface energies described above. The values of γ_{ij} may be determined according to equations (6):

$$\text{Equation (6)} \qquad \gamma_{ij} = \gamma_i + \gamma_j - 2\,\Phi_{ij}\sqrt{\gamma_i \gamma_j},$$

where ϕ_{ij} is a dimensionless interaction parameter that can be computed from the molecular properties of the materials involved, and is close to unity for organic systems.

[0046] As mentioned $\gamma_{S\text{-}L,}$ for example, represents the interfacial surface tension or interfacial energy between the substrate 104 and the droplet 102. The surface energy of the substrate 104 is represented as γ_S. This notation refers to the interfacial surface energy between the material in question (such as substrate 104 in this case) and its saturated vapor.

[0047] Further, if θ_b is 180° - the condition guaranteeing that a lubricating layer 800 separates the insulating layer 104 from the droplet 102 under the above scenario - then cos θ_b equals negative one (-1). In order to design for a contact angle of 180°, then, from Equation (5) comes Equation (7):

$$\text{Equation (7)} \qquad \frac{\gamma_{S\text{-}F} - \gamma_{S\text{-}L}}{\gamma_{L\text{-}F}} \leq -1\text{ , or } \gamma_{S\text{-}F} - \gamma_{S\text{-}L} \geq \gamma_{L\text{-}F}.$$

This concept is best illustrated in FIG. 8, which is a plot of angle θ_b against γ_S of the insulating layer for two different γ_F's - 20mN/m and 16 mN/m, corresponding to lubricating fluids including DMS-T11 silicone oil and DMS-T00 silicone oil, respectively, both manufactured by Gelest, Inc. of Tullytown, Pennsylvania. The plot of FIG. 8 may be generated utilizing equations (5) and (6). The droplet 102 is assumed to be water, with a γ_L of 72 mN/m. From the plot of FIG. 8, assuming a water droplet 102 and a lubricating fluid 802 characterized by a γ_F of 16mN/m, an angle θ_b of 180° is achieved, and equation (7) is also satisfied, if the insulating layer 104 is a material characterized by a γ_S of less than or equal to approximately 26 mN/m (illustrated by dashed line 902). Likewise, assuming a water droplet 102 and a lubricating fluid characterized by a γ_F of 20mN/m, an angle θ_b of 180° is achieved if the insulating layer 104 is a material characterized by a γ_S of less than or equal to approximately 36 mN/m (illustrated by dashed line 904).

[0048] The above example demonstrates that a wide range of materials and their respective deposition techniques can be used if a lubricating liquid assisted electrowetting is employed. Indeed, in order to provide a stick-slip free, low hysteresis behavior without lubricant, a highly uniform, ultra-clean, low-energy surface should be used. This largely confines the available materials to materials such as highly fluorinated hydrocarbons and similar materials. Additionally, the selected material has to be carefully deposited in order to guarantee a required degree of cleanness and surface uniformity. It is possible to overcome those problems, but solutions may involve potentially complicated and costly procedures and equipment. On the other hand, the use of a lubricating layer 800 allows for greater latitude in materials selection since no highly uniform, ultra-clean, low-energy surface is required. For example, if a lubricant with a γ_F of 20 mN/m is employed, a wide range of materials would satisfy the condition that the surface energy γ_S be less than approximately 36 mN/m, including such common polymers as polypropylene, polyethylene, polystyrene, etc. Also, less care need be taken to avoid surface contamination and nonuniformity during the material deposition, thus leading to a simpler and less expensive deposition technique.

[0049] Although the tunable liquid microlenses 600, 700 are shown having the basic structure shown in FIG. 2A, other microlens structures, such as those shown and described in connection with FIGS. 3A-3C, are equally appropriate. Likewise, the tunable liquid microlenses 600, 700 may be used in varied optoelectronic applications, such as those described in connection with FIG. 4 and FIG. 5.

[0050] The tunable liquid microlenses 600, 700 allows for both lens position adjustment and focal length tuning. In addition, the tunable liquid microlenses 600, 700 provide still greater freedom in material selection while providing excellent tunability by avoiding the contact angle hysteresis and stick-slip phenomena.

[0051] Although the invention has been described in terms of exemplary embodiments, it is not limited thereto. Rather, the appended claims should be construed broadly to include other variants and embodiments of the invention which may be made by those skilled in the art without departing from the scope and range of equivalents of the invention.

Claims

1. A tunable liquid microlens, comprising:

an insulating layer;
a droplet of a transparent conducting liquid;
a lubricating layer disposed on a first surface of said insulating layer and between said droplet and said insulating layer; and

a plurality of electrodes insulated from said droplet by said insulating layer and said lubricating layer,
said plurality of electrodes being disposed such that they may be selectively biased to create a respective voltage potential between said droplet and each of said plurality of electrodes,
whereby an angle between said droplet and a plane parallel to said first surface of said insulating layer may be varied and said droplet may be repositioned relative to said insulating layer.

2. The tunable liquid microlens of claim 1, further comprising a droplet electrode for biasing said droplet with respect to said plurality of electrodes.

3. The tunable liquid microlens of claim 2, wherein said droplet electrode includes a conductive transparent substrate disposed along a second surface of said insulating layer, said second surface being opposite said first surface, said insulating layer defining an aperture through said insulating layer whereby said droplet at least partly occupies said aperture and is in electrical communication with said droplet electrode.

4. The tunable liquid microlens of claim 2, wherein said droplet electrode includes:

a conductive transparent substrate disposed along a second surface of said insulating layer, said second surface being opposite said first surface; and
a conductive lead coupling said droplet to said conductive transparent substrate.

5. The tunable liquid microlens of claim 1, wherein said droplet is substantially surrounded by a lubricating liquid that is immiscible with said droplet, said lubricating liquid including said lubricating layer.

6. The tunable liquid microlens of claim 1, wherein said lubricating layer includes a silicone oil.

7. A method of tuning a liquid microlens, said liquid microlens including a droplet of a transparent conducting liquid, an insulating layer, and a lubricating layer disposed on a first surface of said insulating layer and between said droplet and said insulating layer, comprising the step of:

selectively biasing a plurality of electrodes insulated from said droplet by said insulating layer and said lubricating layer to create a respective voltage potential between said droplet and each of said plurality of electrodes.

8. The method of claim 7, wherein said step of selectively biasing includes the steps of selectively biasing said plurality of electrodes to vary an angle between said droplet and a plane parallel to said first surface of said insulating layer and to reposition said droplet relative to said insulating layer.

9. An apparatus, including:

a transmitter, said transmitter providing an optical signal;
a receiver, said receiver receiving said optical signal; and
a tunable liquid microlens disposed to direct said optical signal from said transmitter to said receiver, said tunable liquid microlens comprising:

an insulating layer;
a droplet of a transparent conducting liquid;
a lubricating layer disposed on a first surface of said insulating layer and between said droplet and said insulating layer; and
a plurality of electrodes insulated from said droplet by said insulating layer and said lubricating layer,
said plurality of electrodes being disposed such that they may be selectively biased to create a respective voltage potential between said droplet and each of said plurality of electrodes,
whereby an angle between said droplet and a plane parallel to said first surface of said insulating layer may be varied and said droplet may be repositioned relative to said insulating layer,

whereby a focal length and a lateral position of a focal spot of said microlens are adjusted to direct said optical signal from said transmitter to said receiver.

10. A method of transmitting an optical signal, comprising the steps of:

directing said optical signal from a first location towards a liquid microlens, said liquid microlens including a droplet of a transparent conducting liquid, an insulating layer, and a lubricating layer disposed on a first surface of said insulating layer and between said droplet and said insulating layer; and
tuning said liquid microlens to redirect said optical signal, said tuning step comprising the step of:

selectively biasing a plurality of electrodes insulated from said droplet by said insulating layer to create a respective voltage potential between said droplet and each of said plurality of electrodes.

FIG. 1A

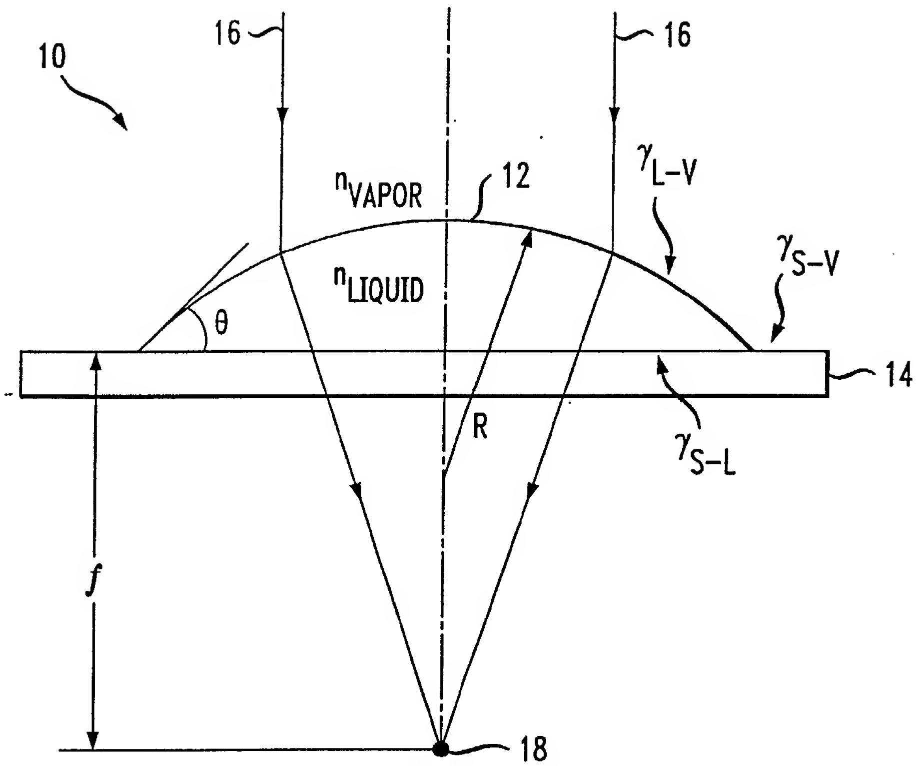

10
16
16
n_{VAPOR}
12
γ_{L-V}
γ_{S-V}
n_{LIQUID}
θ
14
R
γ_{S-L}
f
18

FIG. 1B

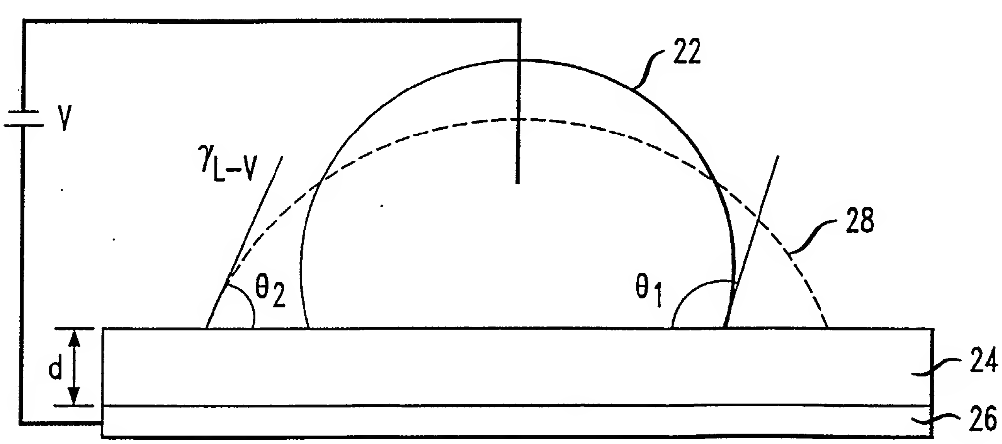

V
22
γ_{L-V}
28
θ_2
θ_1
d
24
26

FIG. 2A

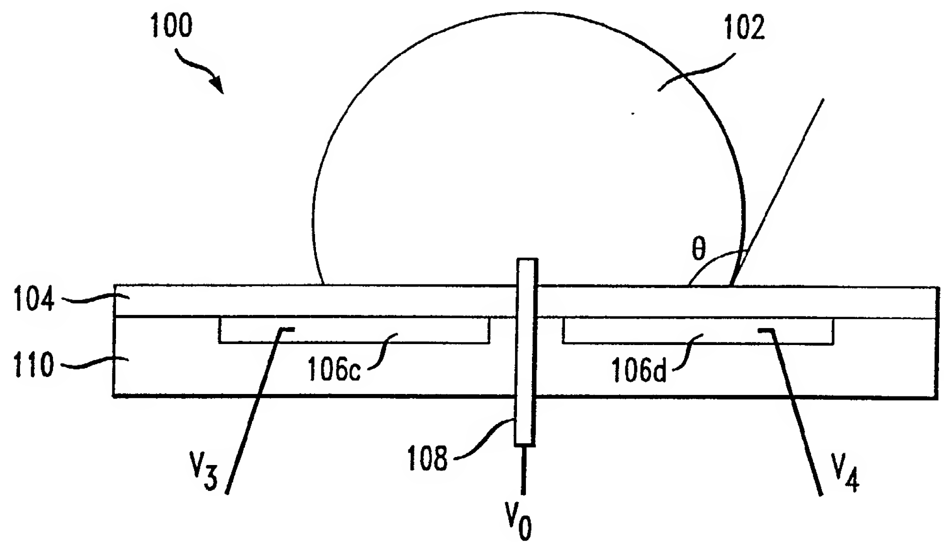

100
102
θ
104
110
106c
106d
V3
108
V4
V0

FIG. 2B

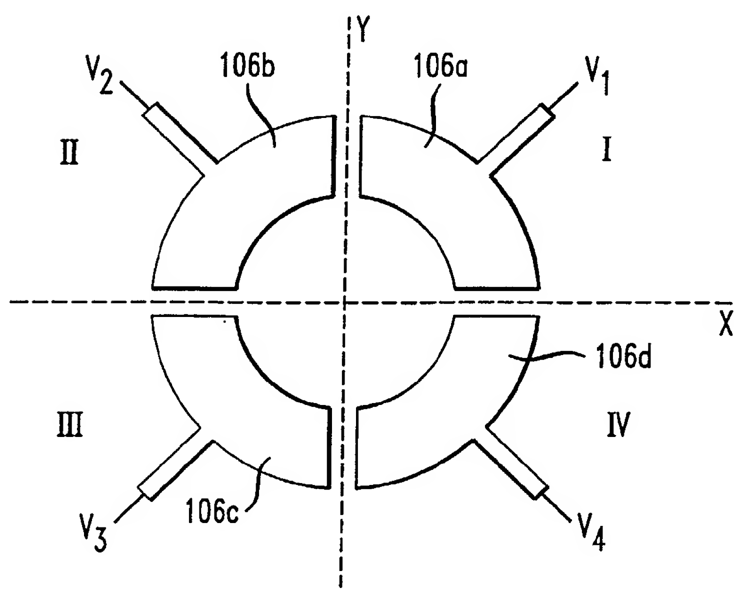

Y
V2
106b
106a
V1
II
I
X
106d
III
IV
V3
106c
V4

FIG. 2C

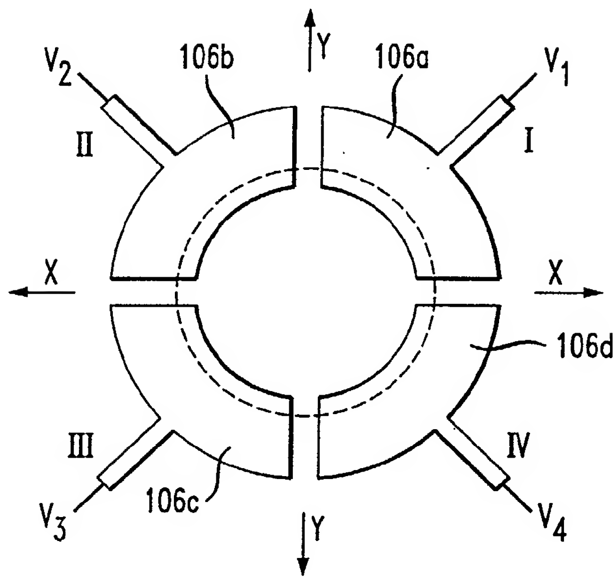

V2
106b
Y
106a
V1
II
I
X
X
106d
III
IV
V3
106c
Y
V4

FIG. 2D

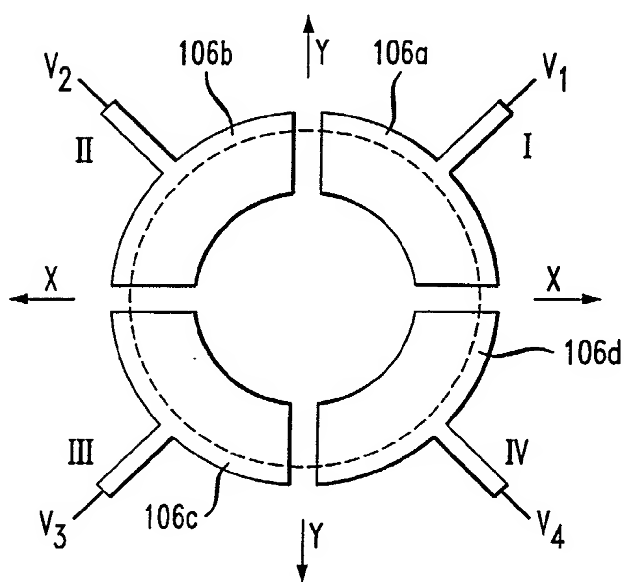

V2
106b
Y
106a
V1
II
I
X
X
106d
III
IV
V3
106c
Y
V4

FIG. 2E

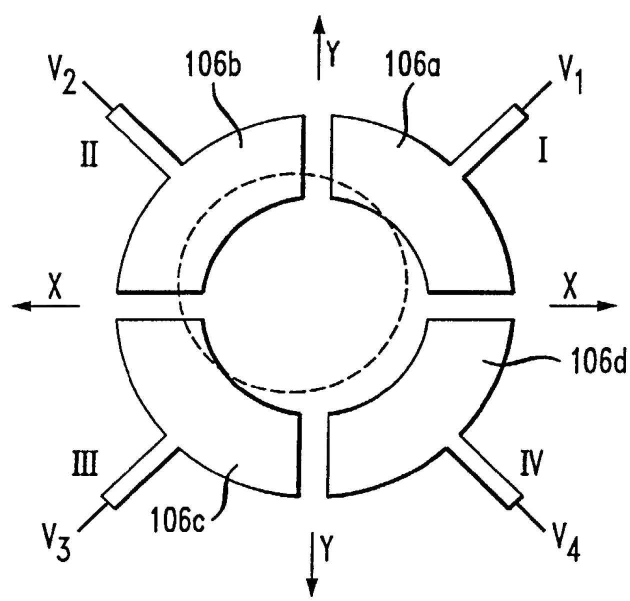


FIG. 3A

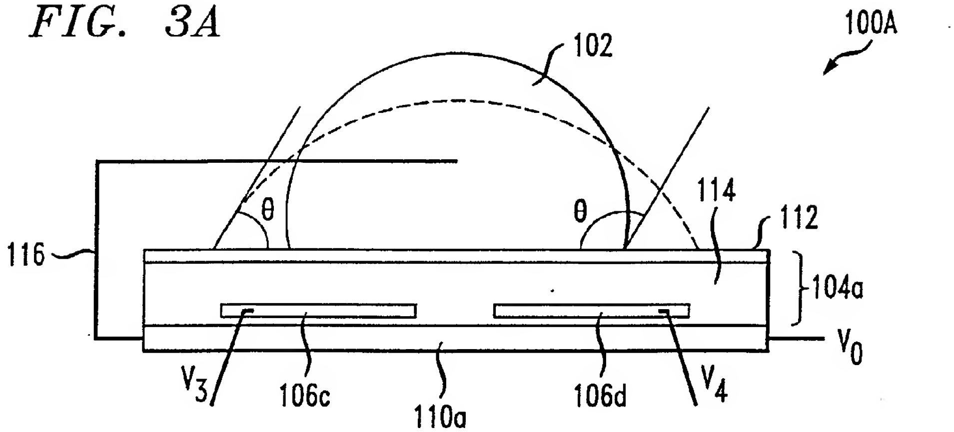


FIG. 3B

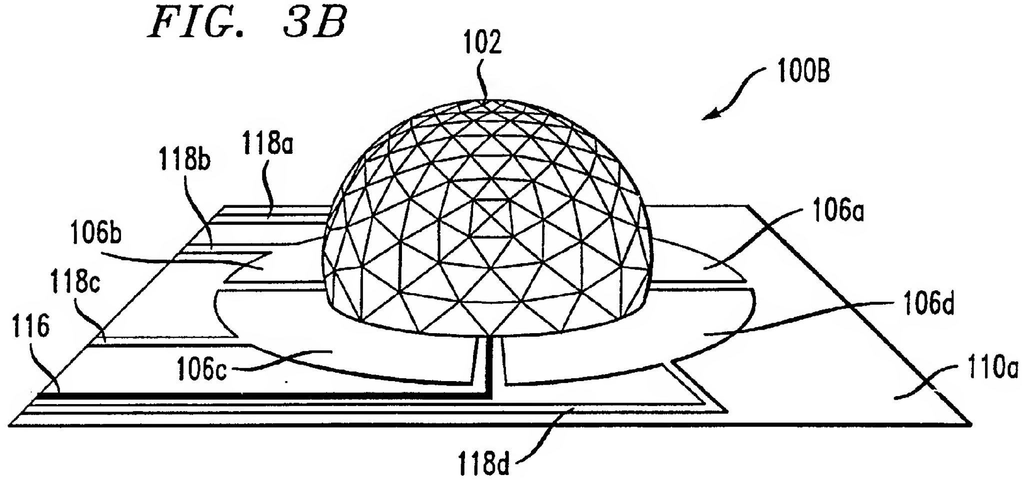


FIG. 3C

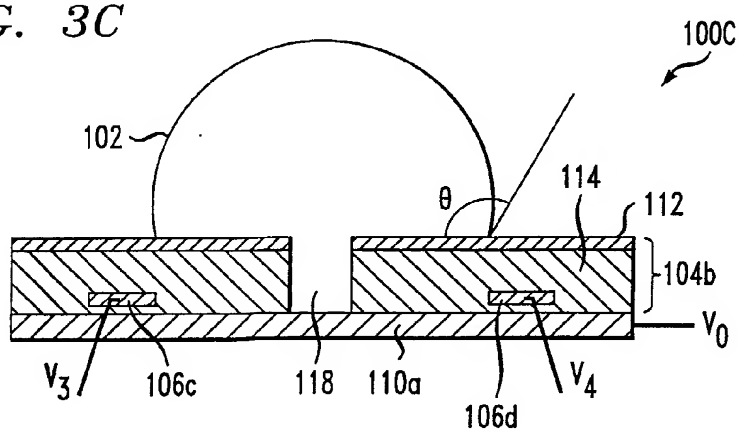


FIG. 4

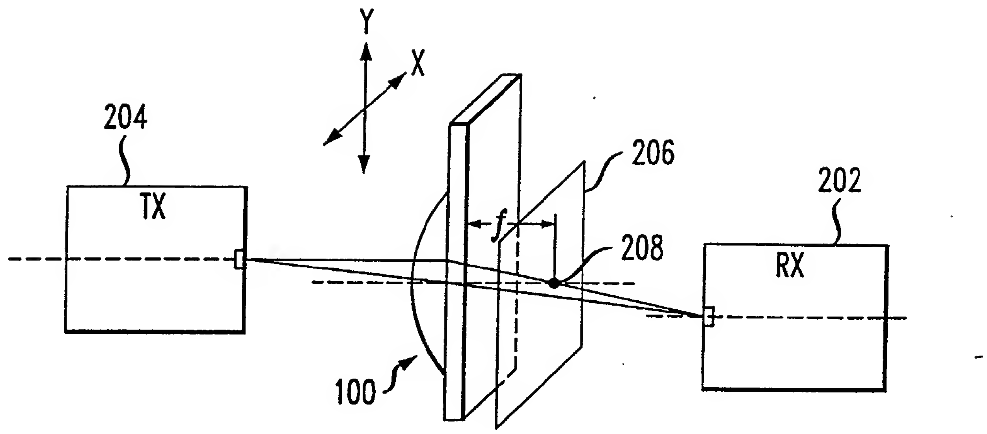


FIG. 5

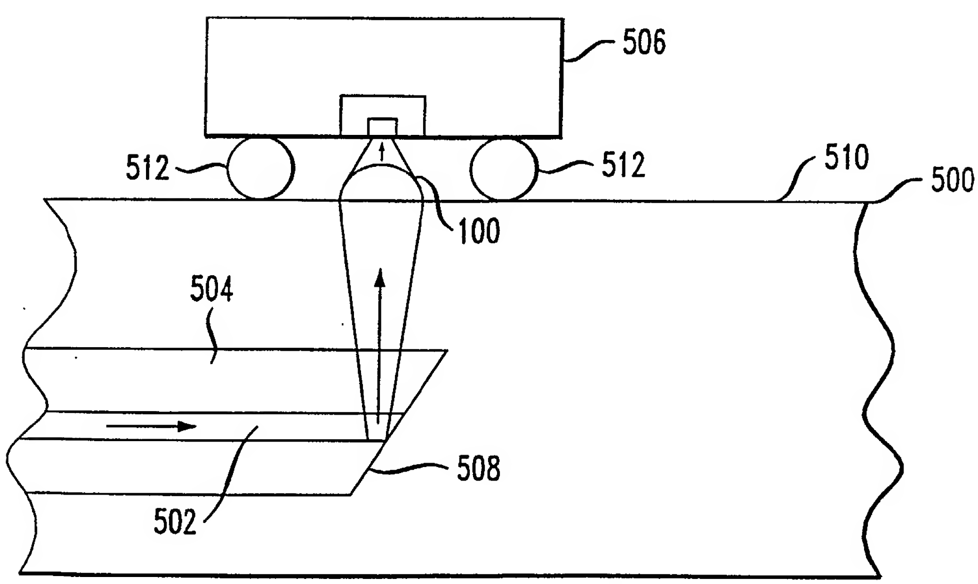


FIG. 6

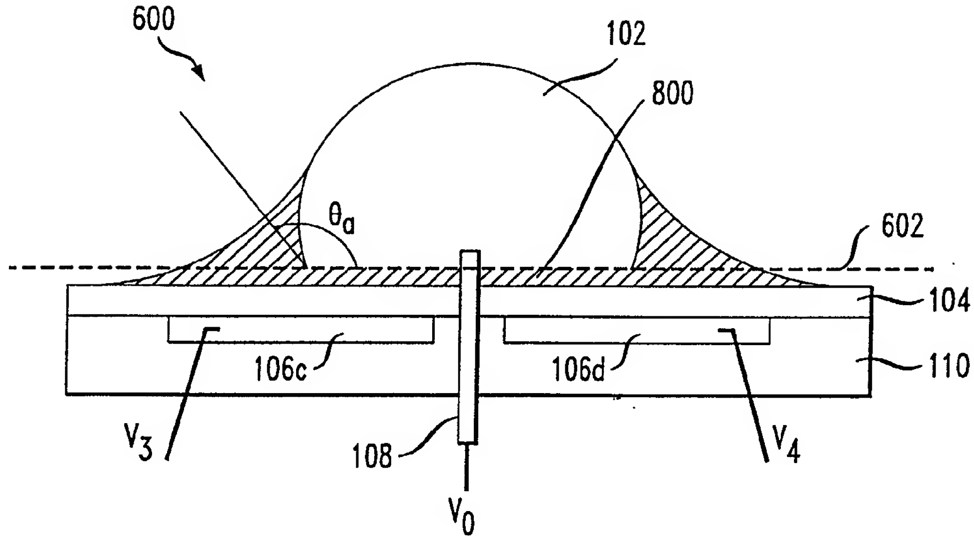

600
102
800
θ_a
602
104
106c
106d
110
V_3
108
V_4
V_0

FIG. 7

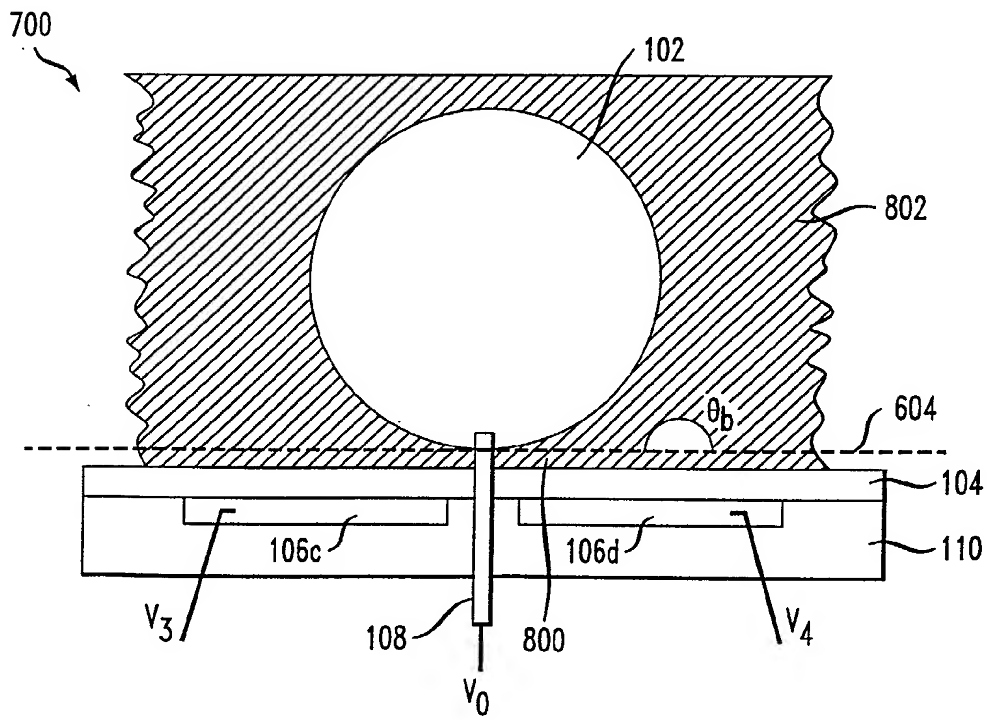
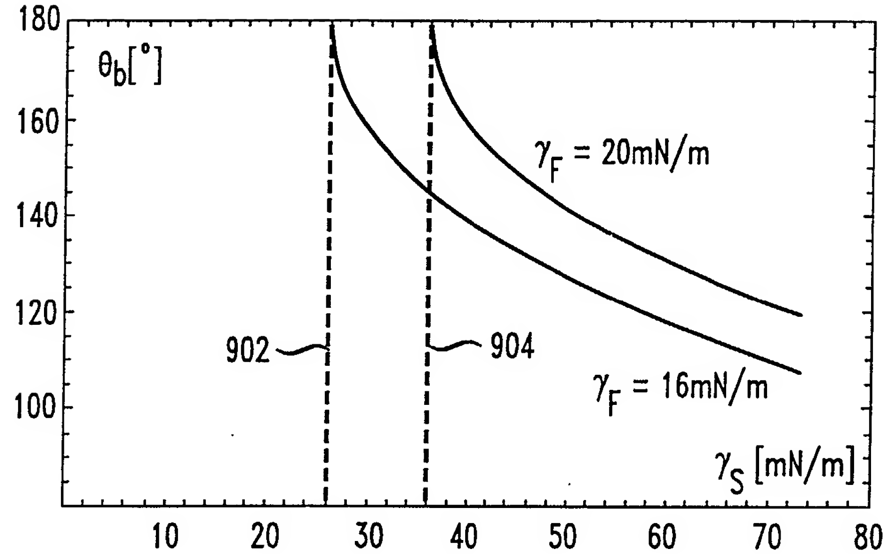

700
102
802
θ_b
604
104
106c
106d
110
V_3
108
800
V_4
V_0

FIG. 8


180
160
140
120
100
θ_b[°]
γ_F = 20mN/m
γ_F = 16mN/m
902
904
γ_S [mN/m]
10
20
30
40
50
60
70
80

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 02 25 2089

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.7)
X	FR 2 769 375 A (UNIV JOSEPH FOURIER) 9 April 1999 (1999-04-09) * page 2, line 3 - line 33 * * page 7, line 23 - page 12, line 13; figures 1,5 *	1-4,7-10	G02B3/14
A	WASHIZU M: "ELECTROSTATIC ACTUATION OF LIQUID DROPLETS FOR MICROREACTOR APPLICATIONS" IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, IEEE INC. NEW YORK, US, vol. 34, no. 4, July 1998 (1998-07), pages 732-737, XP000848012 ISSN: 0093-9994 * the whole document *	1,7,9,10	
A	BERGE B: "ELECTROCAPILLARITE ET MOUILLAGE DE FILMS ISOLANTS PAR L'EAU" COMPTES RENDUS DES SEANCES DE L'ACADEMIE DES SCIENCES. SERIE II:MECANIQUE, PHYSIQUE, CHIMIE, SCIENCES DE LA TERRE, SCIENCES DE L'UNIVERS, GAUTHIER-VILLARS. MONTREUIL, FR, vol. 317, no. 2, 22 June 1993 (1993-06-22), pages 157-163, XP002068041 ISSN: 1251-8069 * the whole document *	1,7,9,10	TECHNICAL FIELDS SEARCHED (Int.Cl.7) G02B
A	EP 1 069 450 A (CANON KK) 17 January 2001 (2001-01-17) * column 3, line 45 - column 7, line 11; figures 1-3C *	1,7,9,10	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	15 January 2003	Sarneel, A

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 02 25 2089

This annex lists the patent family membersrelating to the patent documents cited in the above-mentioned European search report.
The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

15-01-2003

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
FR 2769375	A	09-04-1999	FR	2769375	A1	09-04-1999
			AT	214164	T	15-03-2002
			CA	2306249	A1	15-04-1999
			DE	69804119	D1	11-04-2002
			DE	69804119	T2	28-11-2002
			EP	1019758	A1	19-07-2000
			ES	2171041	T3	16-08-2002
			WO	9918456	A1	15-04-1999
			JP	2001519539	T	23-10-2001
			US	6369954	B1	09-04-2002
EP 1069450	A	17-01-2001	JP	2000356751	A	26-12-2000
			JP	2000356792	A	26-12-2000
			EP	1069450	A2	17-01-2001
			US	6449081	B1	10-09-2002

EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82